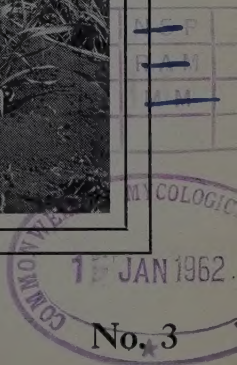


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On the Cover: Net radiometer at Makiki

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MICROCLIMATE OF SUGAR CANE

Jen-hu Chang*

Climates owe their characteristics not only to the large-scale general circulation, but also to the local variations of the flux of heat, momentum, and water vapor between the ground and the atmosphere. The nature of the ground surface thus plays an important role in shaping the micro- and topo-climate of a particular place. Sugar cane, as a tall, ungainly plant, has many microclimatic characteristics quite different from those of bare ground, sod, pineapple, or forest. An understanding of the microclimate of sugar cane would be most useful in determining irrigation-water needs, assessing climatic influence on plant growth and the like; however, microclimatic observations of sugar cane fields are so scanty that little credit can be taken by climatology for the rapid progress of agricultural practices in recent years.

RESEARCH PROGRAM

During the past three years the Experiment Station of the Hawaiian Sugar Planters' Association (HSPA) has conducted an intensive study of the microclimate of sugar cane, with emphasis on evapotranspiration. Four research projects bearing on this subject have been carried out in different localities on Maui and Oahu (*Figure 1*). Inasmuch as these four projects are interrelated, their results will be presented topically in an integrated manner.

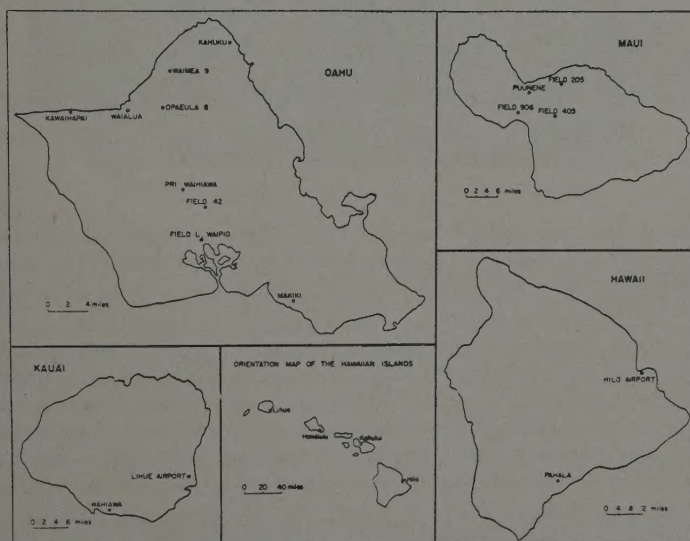


FIGURE 1. Location map.

*Associate Climatologist, Experiment Station, HSPA

1. *Evapotranspiration Project at Hawaiian Commercial & Sugar Co., Ltd. (HC&S).* The objectives of this project are to determine the potential evapotranspiration from a sugar cane field and to assess various methods of estimating potential evapotranspiration from climatic data. The studies have been conducted at three sites at HC&S on Maui: Fields 205, 405, and 906. At each site three drainage lysimeters were installed within the cane field. The lysimeters are tanks 1.52 meters wide, 2.65 meters long, and 1.22 meters deep. At each site, near the lysimeters, are instrument towers on which are mounted hygrothermographs, anemometers, a wind vane, an actinometer, photochemical tubes, a rain gage, and a standard U. S. Weather Bureau Class A evaporation pan (Figure 2). The instrument towers were continually adjusted so that their platforms were always at cane-top levels. Detailed discussion of the instrumentation at these three sites have been given in a previous paper (5).



FIGURE 2. Evapotranspiration experiment site at Field 205, HC&S.

This project was started in April 1957. The plant crop was harvested in November 1958, and the ratoon crop harvested in August 1960. The daily lysimeter and climatic data during this period of some 40 months have been analyzed by IBM computer.

2. *MASI Experiment.* In August 1958 an irrigation experiment was installed at Field 408, HC&S. Its purpose was to test application methods (M), amount of water applied (A), surface shape and cover (S), and irrigation interval (I); hence, the name MASI. This experiment provides two sets of information of interest to agricultural meteorologists: (a) the effects of irrigation on plant growth and yield, and (b) the relationship between pan evaporation and weather elements.

3. *Energy Budget Study at Makiki.* At the Experiment Station, HSPA, incident radiation, albedo, net radiation, pan evaporation, and consumptive use of sugar cane in portable lysimeters have been measured to determine the energy

budget (Figure 3). Various radiation instruments, including pyheliometer, actinometer, photochemical tubes, and blueprint sunshine-recorder were also compared and evaluated.



FIGURE 3. Net radiometer over a sugar cane field at Makiki

4. *Field L Experiment at Waipio.* In September 1960 an experiment was installed in Field L at Waipio in order to evaluate the use of the evaporation pan as a guide to irrigation interval control. The field is divided into six plots. The consumptive-use rates of these plots are assumed to be 1.30, 1.15, 1.00, 0.85, 0.70, and 0.55 times the pan evaporation, respectively, and, when application of these factors to pan evaporation gives an estimation of 2.5 inches total evaporation loss, the field is irrigated. The yield data over a number of years in these plots should permit determination of the most economical level of irrigation.

At Field L the wind profile in the sugar-cane field was measured. Evaporation pans, buried, at the ground level, and elevated to a height of six feet, have also been compared (Figure 4).

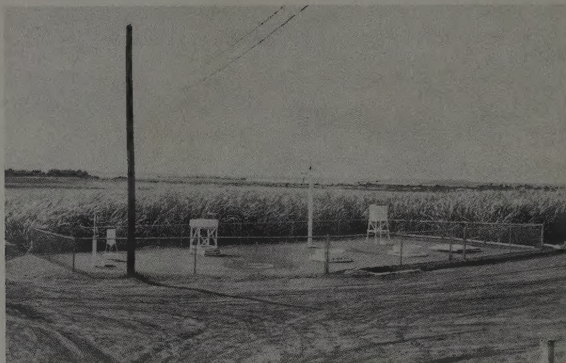


FIGURE 4. Weather instruments at Field L, Waipio.

WIND PROFILE

The effect of a crop of growing sugar cane on the wind profile has been studied at Waipio using the Thornthwaite wind profile instrument. Observations were taken once every month from the planting of the crop to full canopy some six months later.

No attempt was made to evaluate the Richardson number as an indicator of the stability of the atmosphere during the time of observation as recommended by Deacon (9). However, the observation times were carefully chosen so that the atmospheric conditions approximated neutral stability. Furthermore, the instrument was placed at a low height above the crop in order to minimize the stability effect (31).

The records were analyzed by using the simple logarithmic equation rather than the more elaborate Deacon formula. The logarithmic equation reads:

$$u = \frac{1}{k} \sqrt{\frac{\tau}{\rho}} \ln \left(\frac{z-d}{z_0} \right) \quad (1)$$

where u is the wind velocity at the height z ; k , Von Karman's constant; ρ , air density; τ , the shearing stress; d , the zero plane displacement; and z_0 , roughness parameter.

According to equation (1), the wind speed near the ground increases exponentially with height over a very smooth surface. Over a moderately rough surface, e.g. short grass, the logarithmic wind profile holds true only above a hypothetical height z_0 , known as the roughness of the surface. Over a very rough surface like tall vegetation, which acts somewhat like a solid mass, the normal turbulent exchange takes place mainly above a datum level d , the zero plane displacement, which is roughly of the order of the depth of the layer of air trapped among the plants. Both z_0 and d are, therefore, geometric constants of the surface.

Figure 5 illustrates how these two constants increase as the cane grows. For a mature cane 4 meters high the zero plane displacement is 3.5 meters or about 88 per cent of the plant height. By contrast, the zero plane displacement of a tall grass of 65 cm height is only about 30 cm, or less than 50 per cent of the plant height (36).

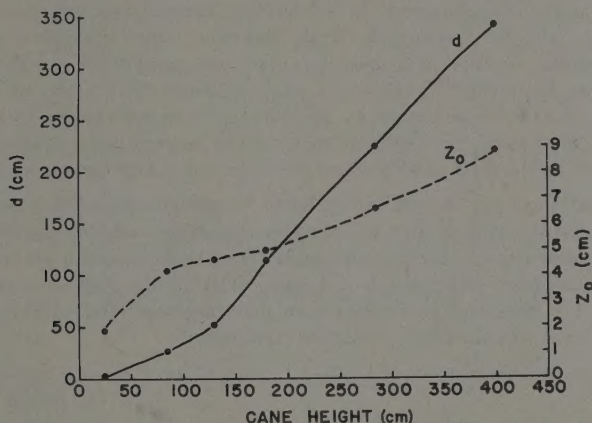


FIGURE 5. Zero plane displacement (d) and roughness parameter (z_0) for the wind profile compared with cane height.

The roughness of a mature cane is about 9 cm as against 2.3 cm for thick grass of 10 cm height, and 0.1 cm for short lawn grass. The high roughness of sugar cane is largely responsible for its high rate of evapotranspiration in areas where advective heat transfer is large (38). This will be discussed in detail in a later section.

It was noticed that, other things being equal, z_0 increases slightly with wind speed. There was also a tendency for d to vary with wind directions. Rider explained that when the wind was directed along the drill lines the value was often smaller than when the wind direction was at right angle to these lines (30).

The high roughness of a tall vegetation also renders the aerodynamic method of estimating evapotranspiration a difficult task (10). This, together with the lack of a suitable instrument for measuring vapor gradient, accounts for the fact that the aerodynamic approach was not assayed in the experiment. The roughness of the surface also exerts an influence on the temperature field. Latta has shown that, other things being equal, an increase in roughness will cause lowering of maximum temperature during daytime and rising of minimum temperature at night (22).

At Field 906, wind speed was recorded at 1 and 2 meters above the cane top. For the period June 1957 to June 1960, the wind speed at 1 meter averaged 173 miles per day as against 207 miles per day at 2 meters.

RADIATION INSTRUMENTS

Although the surface of the sugar cane canopy is not even and smooth, instruments which measure the solar radiation on a horizontal surface seem to be able to satisfy general agricultural needs. An accuracy of 5 per cent seems sufficient for most agricultural studies. For field use, the instruments should also be simple, stable, and reasonable in cost.

The Eppley pyrheliometer is a standard radiation instrument -- sensitive, nonselective, and very accurate. It is, however, very expensive and requires electrical power for recording, and is, therefore, unsuitable for field use. For field use, the Experiment Station has tried at least three kinds of instruments: (a) the actinometer, also known as pyrheliograph, manufactured by the Belfort Instrument Corporation; (b) photochemical tubes using oxalic acid as agent and uranyl sulfate as catalyst; and (c) blueprint sunshine-duration recorder (3).

The actinometer is unreliable. Early in the morning condensation often occurs in the glass dome of the actinometer, possibly causing inaccuracy in the reading. A comparison of the actinometer and pyrheliometer records at HC&S Research Laboratory indicates a seasonal shift of the actinometer calibration (Figure 6). The actinometer consistently underregisters the winter intensity by some 20 per cent, if corrected to summer conditions.

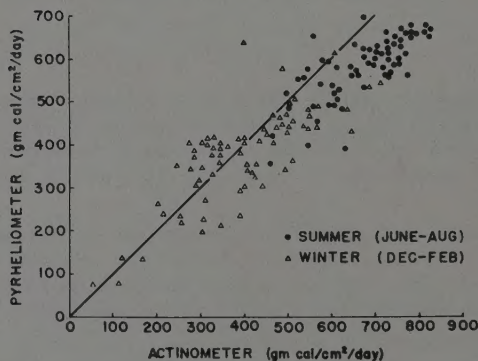


FIGURE 6. A comparison of total daily solar radiation as registered by pyrheliometer and actinometer at HC&S Agricultural Research Laboratory.

The sensing elements of the actinometer are not very accurate. The response to solar radiation varies greatly from one instrument to another; the correlation coefficient of daily solar radiation registered by two actinometers, for

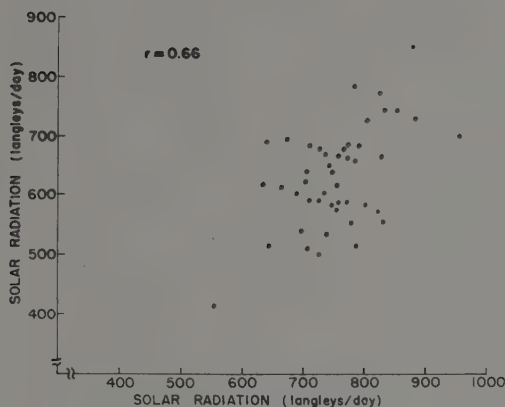


FIGURE 7. A comparison of daily solar radiation registered by two actinometers.

example, was as low as 0.66 (Figure 7). Actinometer records should, therefore, be carefully handled.

The photochemical tubes are much more accurate than actinometers. Almost all the photochemical tubes on the plantations are read weekly. The correlation coefficient of weekly photochemical readings and pyrhelimeter records at Makiki and Waipio are 0.96 and 0.87, respectively (Figures 8 and 9). On the average, the difference between the photochemical and pyrhelimeter readings at Makiki and Waipio are 2 and 4 per cent, respectively.

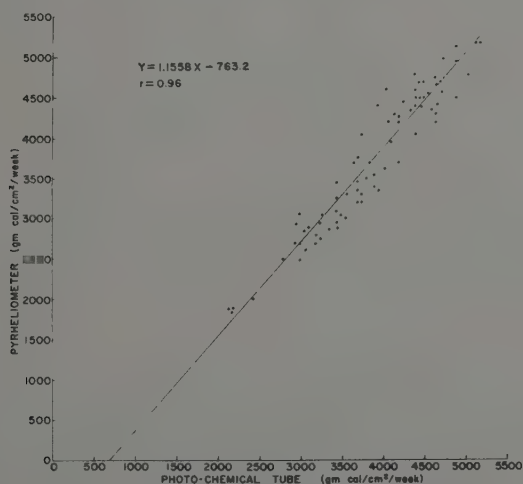


FIGURE 8. A comparison of weekly solar radiation as registered by pyrhelimeter and photochemical tubes at Makiki.

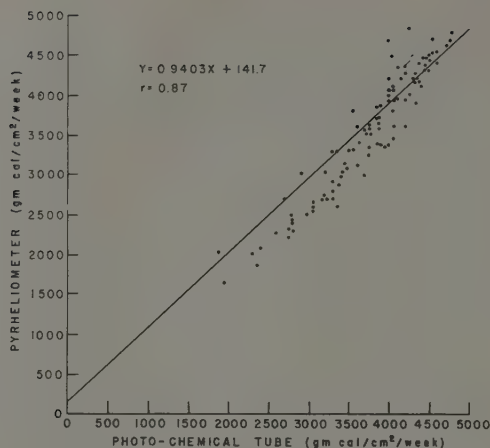


FIGURE 9. A comparison of weekly solar radiation as registered by pyrheliometer and photo-chemical tubes at Waipio.

The blueprint sunshine-recorder gives only the duration of sunshine, which has often been used to estimate radiation intensity. The relationship between the duration of sunshine and radiation intensity varies with the climate and season. In order to obviate the seasonal effect, the solar radiation received at the earth's surface is expressed as a percentage of that at the top of the atmosphere for the specified period. Figures 10 and 11 show the relationship between the percentage of possible solar radiation and percentage of possible hours of sunshine at Makiki and Waipio, respectively. The relationship is much better at Waipio than at Makiki. Makiki is located less than two miles from the Koolau Range and the stratocumuli which usually hang over the range may or may not reflect radiation to Makiki, depending on the cloud condition in the latter area. The presence or absence of this reflected radiation mainly accounts for the wide range of incoming radiation received at Makiki on cloudy days (Figure 10). On the other hand, Waipio is located far from the mountain and is not affected by the reflection from clouds.

It seems that in areas where reflection from clouds is insignificant, the duration of sunshine can be used to estimate the approximate radiation intensity. For Waipio the relationship between sunshine duration and intensity may be expressed in the following form:

$$Y = 0.31 + 0.52 X \quad (2)$$

where Y is the percentage of possible solar radiation and X is the percentage of possible sunshine duration. Equation (2) is only slightly different from the equation established for Kabete, Kenya by Glover and McCulloch (15), which reads:

$$Y = 0.27 + 0.54 X \quad (3)$$

It is probably not unreasonable to assume that for tropical stations not affected by reflection from a semi-permanent cloud bank, approximately the same relationship exists between the sunshine duration and intensity.

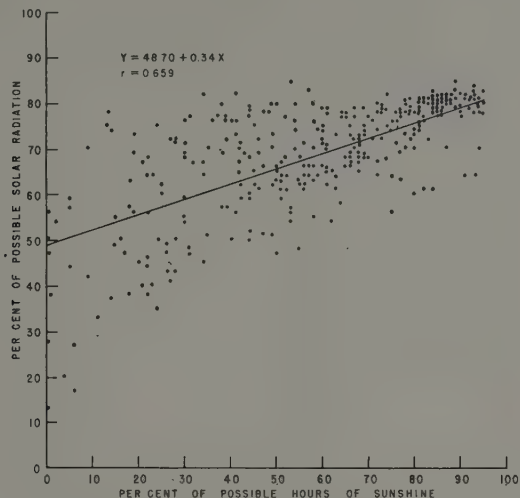


FIGURE 10. Relationship of percent of possible hours of sunshine and solar radiation expressed as a percentage of that at the top of the atmosphere at Makiki.

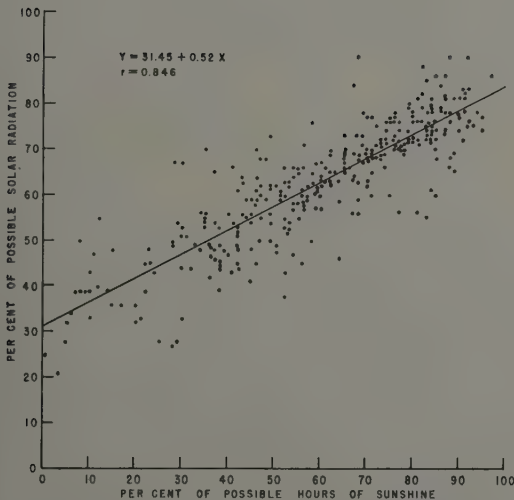


FIGURE 11. Relationship of percent of possible hours of sunshine and solar radiation expressed as a percentage of that at the top of the atmosphere at Waipio.

ALBEDO

The albedo, or reflectivity, of a sugar cane field at Makiki has been measured by an inverted pyrheliometer. *Figure 12* presents the average monthly albedo from August 1959 to July 1960. The albedo of a field of young cane is only slightly higher than that of bare ground, which is about 5 per cent. The albedo increases with the growing crop to an average of 16 per cent or more for a well-developed canopy.

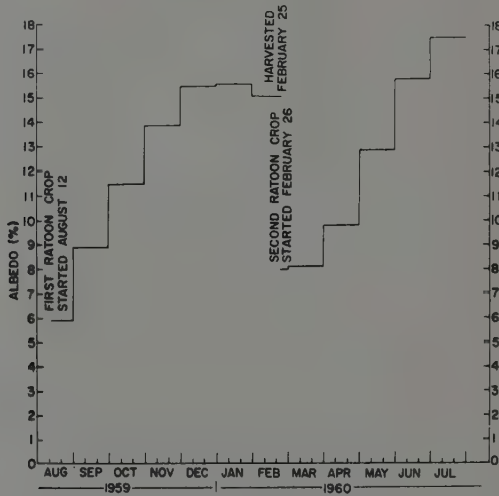


FIGURE 12. The average monthly albedo of a sugar cane field at Makiki from August 1959 to July 1960.

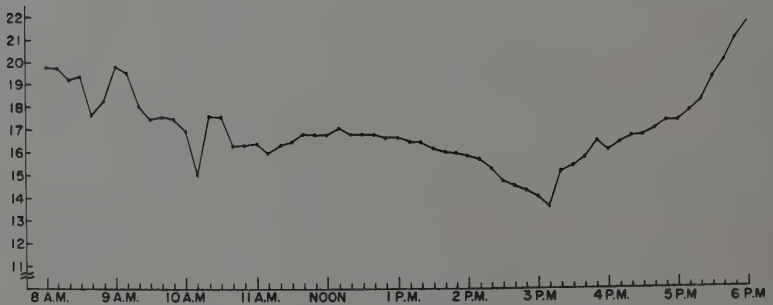


FIGURE 13. Daily course of albedo on a clear summer day at Makiki.

The albedo varies with a number of factors. *Figure 13* shows the change of albedo during the course of a clear summer day. The high albedo in the early morning and in the late afternoon is due to the low angle of incidence. This

agrees with observations taken at O'Neill, Nebraska (44). However, this increased reflectivity is probably only partly real and partly caused by the specular characteristics of the Eppley pyrheliometer as pointed out by Fuquay and Buettner (13).

The albedo usually decreases after a rain which darkens the surface. On the average, the albedo on a rainy day is about 2 or 3 per cent lower than that on a clear day. The color of the crop also affects the albedo to some extent.

NET RADIATION

The part of incident radiation that is not reflected or re-radiated back to the atmosphere is called net radiation. It is actually the difference between the incoming and outgoing radiation, and hence represents the energy available for plant use.

Net radiation has been measured at Makiki by a Beckman-Whitley Model N-188 net radiometer. This instrument is inaccurate when its surface is cooled by rain; therefore, records on rainy days are not used. Readings of net radiometer are also affected to some extent by the wind speed and wind direction with respect to the sensing elements (28).

The ground usually loses energy at night. At Makiki the net radiation at night is in the neighborhood of $-0.1 \text{ gm cal/cm}^2/\text{min}$ (or langley/min) throughout the year. The outgoing radiation equals incoming radiation about an hour after sunrise and an hour before sunset (Figure 14). During the daytime, net radiation may even exceed the incident radiation for a short period when the sky is partially cloudy but when the clouds are not directly overhead. During such periods the incoming radiation is augmented by the reflected radiation, while the outgoing radiation is checked by the clouds. Occasionally the maximum net radi-

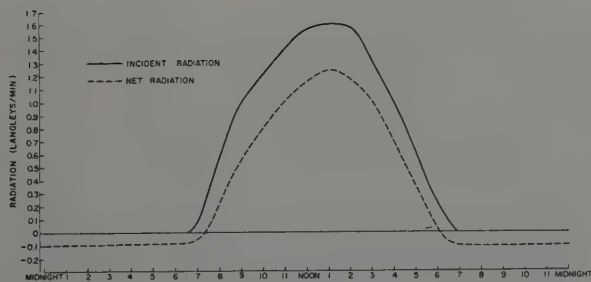


FIGURE 14. Daily course of incoming and net radiation on a summer day at Makiki.

tion may exceed 1.8 langleys/min, the upper limit of the recorder at Makiki. Portman* has noted that the maximum net radiation recorded by the Beckman-Whitley radiometer may reach as high as 2.0 langleys/min, the value of solar constant.

Figure 15 shows the relationship between total daily incoming and net radiation from August 1959 to July 1960. The correlation coefficient was 0.95. The percentage of net to incident radiation varies from 68 per cent in summer to 65 per cent in winter, the average being two-thirds. This figure is in exact agreement with the observations taken over sod by the Pineapple Research Institute (PRI) at Wahiawa. At Ames, Iowa (34) and at Wageningen, Netherlands (33) the net radiation is about 68 to 75 per cent of the incoming radiation during the summer. At Centerton, New Jersey, the percentage is, however, only about 55 on clear summer days (11). During the cold season in middle and high latitudes, the outgoing radiation is so excessive that the net radiation is often negative.

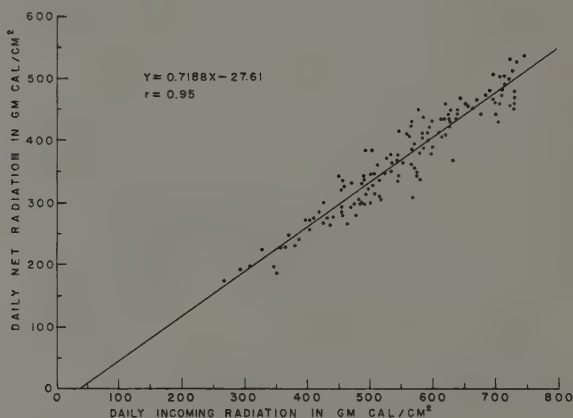


FIGURE 15. Relation between daily incoming and net radiation at Makiki.

The outgoing radiation depends upon the temperature of the ground, the cloudiness, and the vapor pressure of the air. The radiation loss, R_b , may be approximated by the equation of the form (4):

$$R_b = \sigma T^4 (a - b \sqrt{e}) (c - fN) \quad (4)$$

where σ is the Stefan-Boltzmann constant; T , absolute temperature of the ground; e , vapor pressure of the air; N , the cloudiness; a, b, c, f , are constants.

*D. J. Portman, Research Meteorologist, University of Michigan, oral communication.

As cloudiness increases, both incoming and outgoing radiation decreases. Also as incoming radiation decreases, the temperature decreases and this in turn decreases outgoing radiation. The factors which change incoming radiation change outgoing radiation in the same way so that the net radiation, which is the difference between the two, is subject to less change. In this connection, as pointed out by Pelton *et al* (25), the net radiation is a conservative element which makes it all the more useful in agricultural meteorology.

ENERGY BUDGET

Over a mature cane field the partition of incoming radiation is approximately as follows: 16 per cent reflected radiation, 17 per cent back radiation, and 67 per cent net radiation (Figure 16). The net radiation received at the ground surface is further disposed of in three ways: heat flux to the soil, heat flux to the air, and the energy used in evapotranspiration. In the tropics, especially under the cover of a tall vegetation, the heat flux into and out of soil is usually so small that it can be neglected. Thus the energy budget equation can be solved by measuring either the evapotranspiration or the energy used in heating the air.

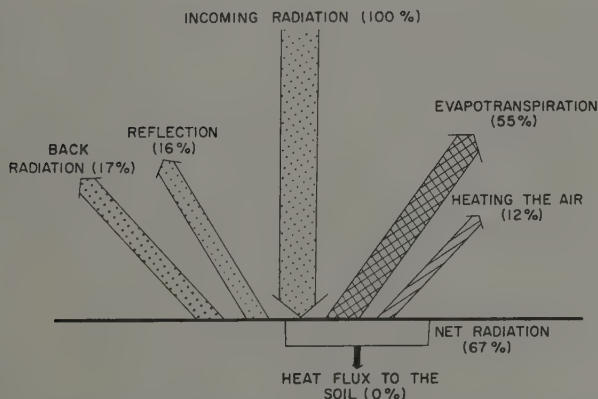


FIGURE 16. Energy budget over a sugar cane field at Makiki.

In the Makiki experiment, on an annual basis, 82 per cent of the net radiation, or 55 per cent of the incoming radiation, is consumed in evapotranspiration, leaving 12 per cent of the insolation for heating the air (Figure 16). Graham and King (16) reported that a corn crop near Guelph, Ontario used about 81 per cent of the net radiation in summer. Noffsinger and Nunns (24) estimated that in Hawaii approximately 60 per cent of the insolation is used in evapotranspiration during a 12-month period of alfalfa production.

The percentage of insolation used for evapotranspiration is, however, subject to seasonal variation. Records at Makiki for the period 1958-60 indicate

that the percentage varies from 57 in September to 47 in January (*Figure 17*). Since the net radiation accounts for 68 percent of the insolation in summer and 65 per cent in winter, the percentage of incoming radiation used in heating the air would vary from 11 per cent in summer to 18 per cent in winter.

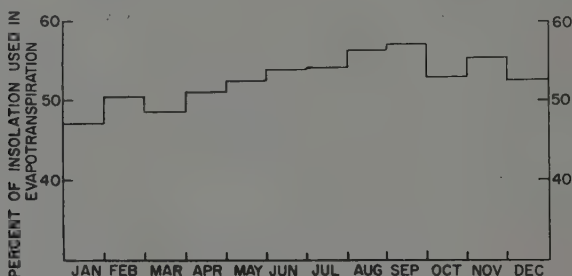


FIGURE 17. Monthly variation of the percentage of insolation used in evapotranspiration.

The energy budget presented here is very crude and gives only the approximate values. The energy used in photosynthesis, for instance, is ignored in the equation. G. O. Burr of the Experiment Station, HSPA, has observed that the part of incident radiation used for photosynthesis by sugar cane averages about 2 per cent and may reach 4 per cent for short periods. Another item that may change the balance of the equation is the advective heat which is extremely difficult to measure or estimate. Since Makiki is located in an area relatively free from advection, the energy budget equation should be fairly accurate. Records at Waipio also indicate the same energy partitioning as at Makiki. However, the radiation-evapotranspiration relationship may be somewhat different in areas where advective heat is significant, e.g. HC&S on Maui.

TEMPERATURE AND HUMIDITY FIELDS

At Field 405, HC&S, temperature and humidity were measured over the cane field and at about 20 meters upwind over sparse grass. Both measurements were taken at a height of 2 meters above the vegetation surface; the grass, however, was not irrigated.

For the period July 1957 to June 1958, the average maximum and minimum temperatures over the cane field were lower than those over the sod by 1.4° and 1.2° C., respectively. Differences in the maximum temperatures were slightly higher in the summer than in the winter, while the differences in the minimum temperatures were reversed (*Figure 18*). The average daily temperature range was 0.4° C. lower over the cane field than over the grass; this can be explained at least in part by the high roughness of the sugar cane.

Both the maximum and minimum relative humidity averaged higher over the cane field than over the sod (*Figure 19*). The differences were greater during

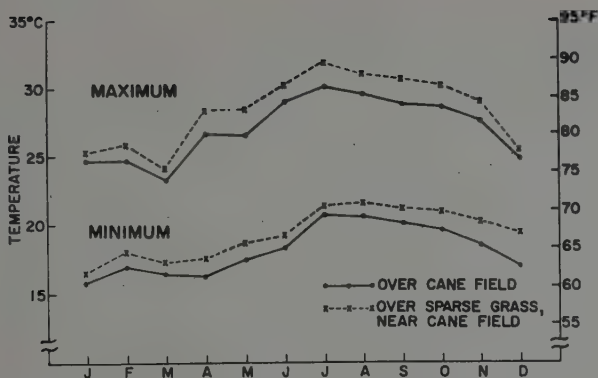


FIGURE 18. A comparison of the maximum and minimum air temperatures over a cane field and over sparse grass.

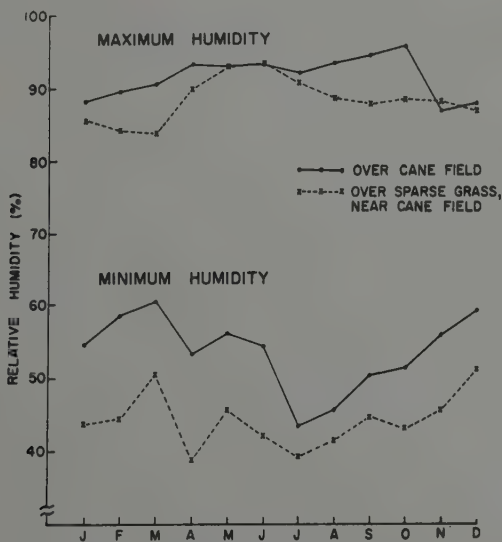


FIGURE 19. A comparison of the maximum and minimum humidity over a cane field and over sparse grass.

the day, when the evapotranspiration process is in full sway, than at night. The average annual minimum humidity was 9.4 per cent and the maximum 3.2 per cent higher over the cane field than over the sod.

At Field 906, temperature and humidity were measured at 1 meter and at 2 meters above the cane top. Both the average temperature and the humidity decreased upward. For the three-year crop period, the average temperature was 24.1°C(75.3°F) at the 1-meter level, as against 23.8°C(74.9°F) at 2 meters; the relative humidity was 73.3 per cent at 1 meter and 72.5 per cent at 2 meters.

PAN EVAPORATION AS A CLIMATIC PARAMETER

The usefulness of the evaporation pan as an indicator of the consumptive use by plants has been hotly debated. Under arid or semi-arid conditions of the Great Plains, free water evaporation bears little relationship to evapotranspiration from wheat (1,35). In Australia, where arid climate prevails in most of the continent, Hounam has found that pan coefficients vary widely according to geographical location (18). In an arid climate, the pan evaporation is accentuated by the oasis effect to such an extent that its usefulness as a climate parameter is greatly impaired.

In a humid climate, water use by crops well supplied with water has been related to free water evaporation by many investigators. Suzuki and Fukuda (37) have shown that in Japan pan evaporation correlated well with evapotranspiration from upland rice and barley. They further demonstrated that pan evaporation is a more accurate indicator of the consumptive use than the Thornthwaite (40) or Blaney and Criddle (2) methods. In British Columbia, Krogman and Lutwick (20) have used pan to determine the irrigation levels that will produce the highest yields for forage crops. In England, Penman (26) has not only derived a formula for estimating free water evaporation, but has also related it to consumptive use by sod. His approach has been successfully applied elsewhere in humid climates.

Theoretically, when the water supply is ample, evapotranspiration by a given crop approaches a maximum value dependent *primarily* on climate. In a humid climate, where the oasis effect upon the free-water surface evaporation is minimized, pan evaporation, also being a direct function of climate, would logically be related to evapotranspiration. In the trade-wind climate of Hawaii, where the air below the inversion layer is humid throughout the year, van't Woudt (42) has rightly stressed the usefulness of pan evaporation as a climatic parameter.

It is true that evaporation from a pan varies with its size, color, material, exposure, depth and the like. The relationship between the pan size and the evaporation rate, however, can easily be determined (45). Furthermore, the effect of pan size on evaporation decreases with high wind (43), which is the prevailing condition in Hawaii. The differences in evaporation between a white and a black pan may reach 23 per cent (46); a copper pan would evaporate some 10 per cent more than an aluminum pan (46); however, all these variances can be obviated by using the same kind of pan and maintaining it properly.

Exposure exerts an important effect on evaporation. Records at Fields 205, 405, and 906 indicate that pans at the cane-top level evaporate some 5 per cent less than pans located outside the cane field, over sod where the environment is drier. At Waipio, the pan elevated to approximately the cane-top level evaporated 10 per cent more than a ground-level pan, and 28 per cent more than a buried pan during the period from August 1960 to March 1961. The exceedingly low evaporation rate from the buried pan is caused not only by the low wind near the ground, but also by the high moisture content of the irrigated plot, which keeps the ground cool. Konstantinov reported that a sunken pan evaporated more than a ground-level pan during the summer at Valdai, USSR (32); however, he did not specify the moisture condition of the ground. It seems reasonable to assume that the moisture content of the soil plays an important

role in determining the ground as a heat source or heat sink.

Since the elevated pan most closely approximates the condition at the cane canopy, it is suggested that, for estimating consumptive use of sugar cane, evaporation pans be elevated. However, the effect of exposure and installation on evaporation needs further study.

In recent years soil physicists have made progress in methods for measuring soil moisture content such as the neutron scattering method, gypsum blocks, tensiometers, etc. It is conceded that soil moisture deficiencies measured by some of these methods are more accurate than those computed from evapotranspiration estimates derived from pan evaporation rates. However, the pan evaporation approach may have two distinct advantages over the soil moisture approach in irrigation planning and scheduling. First, the evaporation and rainfall records can be readily used to estimate the drought probabilities and hence the general irrigation requirements of a particular locality. Secondly, in areas where water deficiencies occur only during short period of the year, pan operation may prove to be more economical and convenient than programs of measuring soil moisture content.

PAN EVAPORATION AND WEATHER ELEMENTS

The U. S. Weather Bureau Class A pan, being recommended by the World Meteorological Organization as the international standard, has been used in the experiments. The pan evaporation data in the evapotranspiration project at HC&S have been compared with the weather elements according to the Thornthwaite and Penman methods.

Thornthwaite expressed the potential evapotranspiration as a function of the mean monthly air temperature and applied a day length adjustment to correct the relation for season and latitude. The HC&S data indicate that the Thornthwaite estimate is, on the average, only 54 per cent of the pan evaporation, the differences being especially large in summer (*Figure 20*). The Thornthwaite estimates also show a lag of about a month behind the pan evaporation. The inadequacies of temperature as a measure of available energy and the limitations of the Thornthwaite approach in a tropical maritime climate have been discussed elsewhere (6).

Penman combines the energy budget and aerodynamic approaches in a formula for estimating evaporation from temperature, wind, humidity, and radiation. His equation takes the form:

$$E = \frac{\Delta H + \gamma E_a}{\Delta + \gamma} \quad (5)$$

Where E = evaporation from open water surface,

Δ = de_a/dT

H = net radiation

$E_a = 0.35 (1 + 0.54 u) (1 - h) e_a$

γ = 0.486 (the psychrometric constant)

e_a = saturation pressure of water vapor at temperature T

T = temperature

h = relative humidity

u = wind speed at 2 m height

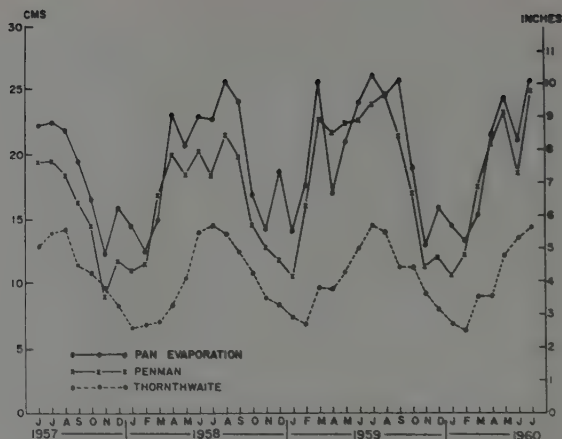


FIGURE 20. Pan evaporation at Field 906 as compared with the Penman and Thornthwaite estimates.

Since the net radiation is not commonly observed, Penman used the Brunt formula which estimates net radiation from sunshine duration, humidity, and temperature. Instead we used the empirical relationships between the net and incoming radiation in our computation (Figure 15).

The Penman estimates agree well with the observed monthly pan evaporation (Figure 20). The correlation coefficient is 0.86. On the average, the Penman value is 89 per cent of the pan evaporation, with lower values in the winter.

Gilbert and van Bavel asserted that the Penman method does not apply to periods of less than five days (14). The coefficients of correlation between Penman's estimates and the pan evaporation at Field 908 were 0.62, 0.78, 0.81, 0.84, 0.85, and 0.86 for 1-, 3-, 5-, 7-, 10-, and 30-day periods respectively. It is shown that the Penman estimates become quite stable after reaching a period of seven days; this is of practical significance in irrigation scheduling because the irrigation intervals are almost always longer than seven days.

In the classical Lake Hefner study, Kohler *et al* (19) suggest the use of $(0.5 + 0.54u)$ instead of $(1.0 + 0.54u)$ in the wind function. Our records indicate that the Lake Hefner constant would lower the Penman estimates by 3.3 per cent, but the correlation coefficient would be practically the same.

The climatic records at 1 and 2 meters above the cane at Field 906 were also compared to the Penman equation. The results show that evaporation at the 2-meter height would exceed that at 1 meter by 3.5 per cent. This further underlines the importance of installing the pan at proper and uniform height.

In equation (5) the ΔH term is more important than the γE_a term. Ordinarily the value of the latter is less than one-fourth that of the former; in other words, radiation is considered the primary factor of the evaporative process. In-

deed, the correlation coefficient between the monthly pan evaporation and incident radiation at Field 906 is as high as 0.86, the same as that between the Penman estimate and pan evaporation.

EVAPOTRANSPIRATION AND PAN EVAPORATION

The daily evapotranspiration of mature sugar cane, as recorded by the lysimeters at HC&S, was about 0.3 to 0.5 cm in winter and 0.7 to 0.9 cm in summer. The annual consumptive use for the three fields varied from 200 to 240 cm, or approximately 80 to 95 inches.

Figure 21 shows the average evapotranspiration/pan evaporation ratios with respect to the cane age for both the planted and ratoon crops for all three fields. The ratio increased from 0.40 for young cane to 1.01 when the canopy is fully developed at the age of five months. The ratio reaches a peak of 1.20 when the cane is 10 months old, followed by a gradual decrease to 0.98 seven months later, and a subsequent rise before the cane is harvested.

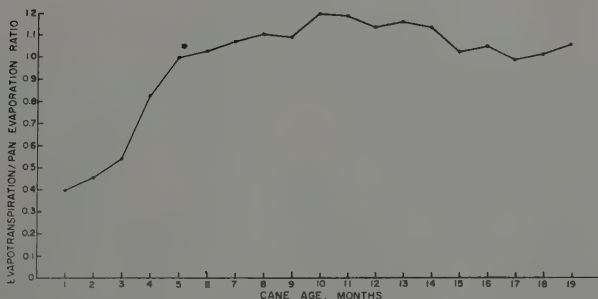


FIGURE 21. Average evapotranspiration/pan evaporation ratios from the three HC&S fields compared to age of cane.

This general trend of consumptive use is not unlike that observed in many other crops. Hall has found in gherkin that, with maturation, subsequent transpiration rates fell rapidly (17). Lemon *et al* reported that the evapotranspiration rate of a cotton crop planted in May rose to a distinct peak in August, then fell off rapidly in September (21).

The increase of the cane evapotranspiration/pan evaporation ratio during the first 10 months may be explained by the increased leaf area and plant height which, in turn, increases the available energy. The fluctuations in evapotranspiration after 10 months, however, cannot be explained by energy budget and are probably physiological in origin.

The average cane evapotranspiration/pan evaporation ratio at HC&S is 0.98 for all cane ages and 1.08 for the mature cane after it is four months old. Penman (27) has observed, and Neumann (23) has confirmed theoretically that

the ratio of the annual evapotranspiration from a short grass to evaporation from a British buried pan should be about 0.75. The high ratio for sugar cane may be accounted for, at least in part, by the high roughness of the cane surface in an area of strong advection. In this connection it should be pointed out that crops are more affected by advected heat than is water in a pan. The smooth surface of water protected by the pan's rim is not as good an interceptor of warm air moving into the area as are crop surfaces, which are rough and protrude.

The ratio of 1.08 seems reasonable in comparison with the evapotranspiration studies of some other tall crops. Lemon *et al* found that, in Texas, well-watered cotton can use an amount of water at least as great as evaporation from the Class A pan (21). Fritschen (12) reported an evapotranspiration/pan evaporation ratio of about 0.87 for mature corn in Iowa. In Japan, the evapotranspiration/pan evaporation ratio of upland rice has been found to be 1.20 (27). In Natal, Cleasby (7) reported that evapotranspiration from sugar cane appears to be considerably higher than Penman's factor, although he did not give any specific figure. However, Cowan and Innes obtained a ratio as low as 0.6 for mature cane in Jamaica (8). It is difficult to reconcile the difference between the Jamaica data and other results mentioned, except to point out that the physiology of the cane, the cane height, the lysimeter border effects, and the design and exposure of pans all would affect the ratio.

WATER BALANCE STUDY

Since there is a definite relationship between pan evaporation and consumptive use of sugar cane, pan evaporation records can be used to indicate the water need of an area for the growth of sugar cane. Pan evaporation has been recorded in more than 20 stations on Hawaiian sugar plantations. *Figures 22-37* portray the monthly pan evaporation and median rainfall for 16 Hawaiian stations where more than one year's record is available.

The median rainfall is used instead of the mean because it is a more useful quantity in expressing the "normal" condition. The frequency distribution of monthly rainfall values in the Hawaiian Islands is very skewed, i.e., a very few large values outweigh a great many rather small values. Riehl (29) has pointed out that in many tropical areas, except on mountain peaks, rainfall derived from the 50 per cent of the days with least rainfall amounted to only 10 per cent of the total, while the 10-15 per cent of the days with the heaviest rain accounted for 50 per cent of the rainfall. Therefore, the median rainfall is not only lower than the mean, but also more accurately represents the effective rainfall for crop use.

In the water balance graphs, the difference between pan evaporation and median rainfall represents the approximate water deficit of the area, and hence it is in some degree a measure of the agricultural potential. Stations at HC&S, as a group, have the highest water deficit, i.e., 59 to 86 inches per year; most of the pan stations on Kauai and Oahu have deficits ranging from 25 to 45 inches. It should also be emphasized that in some of the unirrigated stations on Hawaii, e.g., Pahala, water deficits do occur in the summer months.

The MASI experiment showed that 12 acre-inches of effective irrigation water would increase the yield by a ton of pol. Thompson (39) has reported that the response to irrigation in Natal at the rate of 28 inches of water per two-

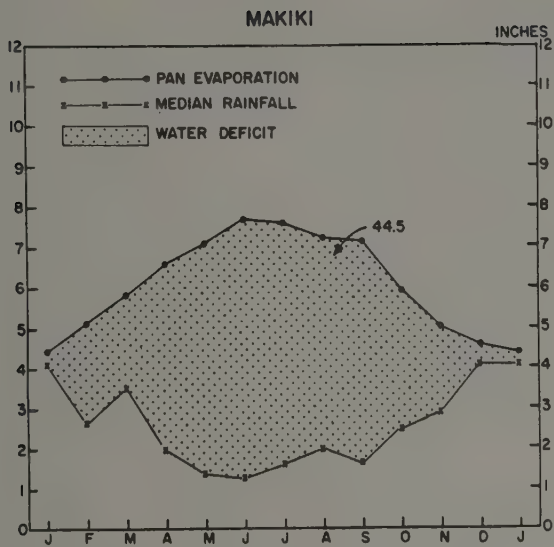


FIGURE 22. Monthly water balance chart at Makiki.

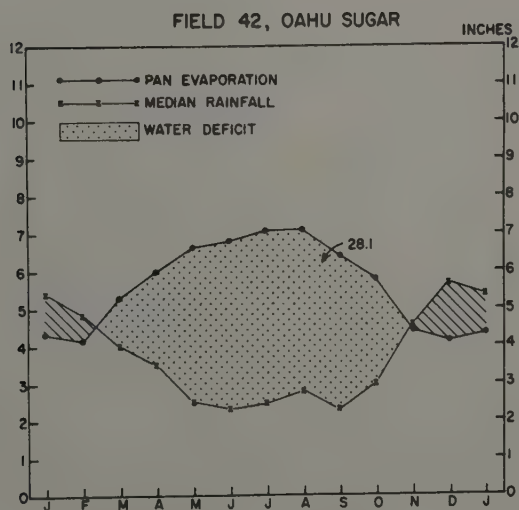


FIGURE 23. Monthly water balance chart at Field 42, Oahu Sugar.

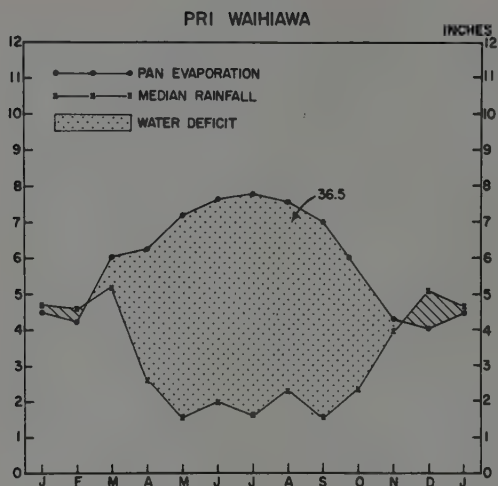


FIGURE 24. Monthly water balance chart at PRI Waihiawa.

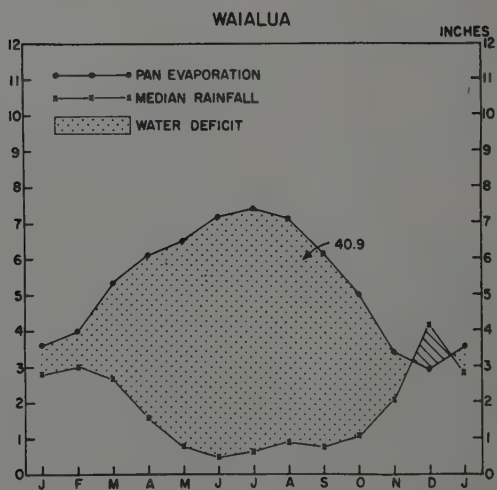


FIGURE 25. Monthly water balance chart at Waialua.

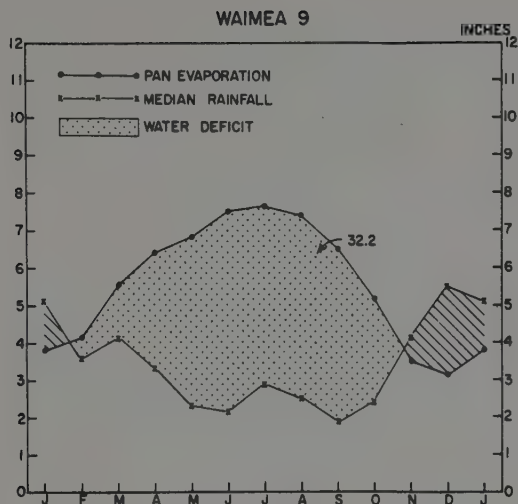


FIGURE 26. Monthly water balance chart at Waimea 9.

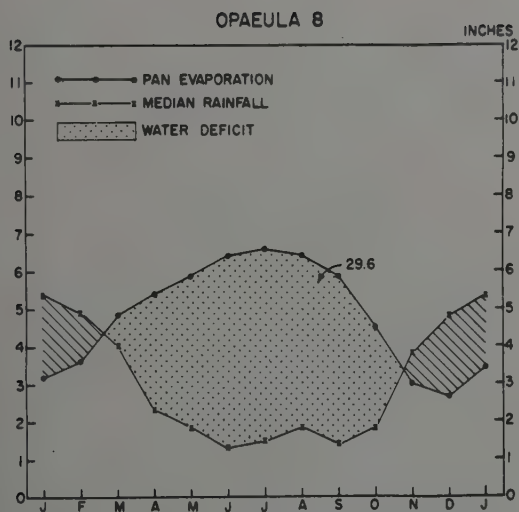


FIGURE 27. Monthly water balance chart at Opaëula 8.

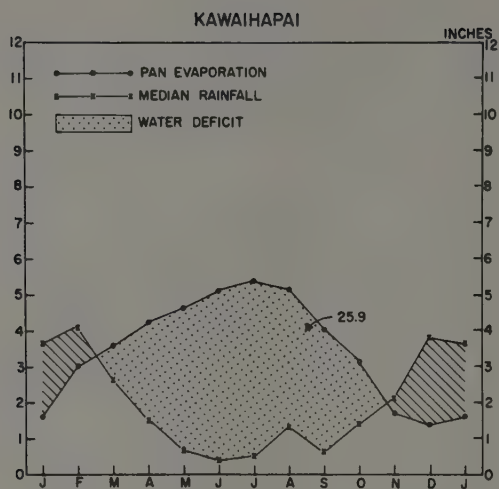


FIGURE 28. Monthly water balance chart at Kawaihapai.

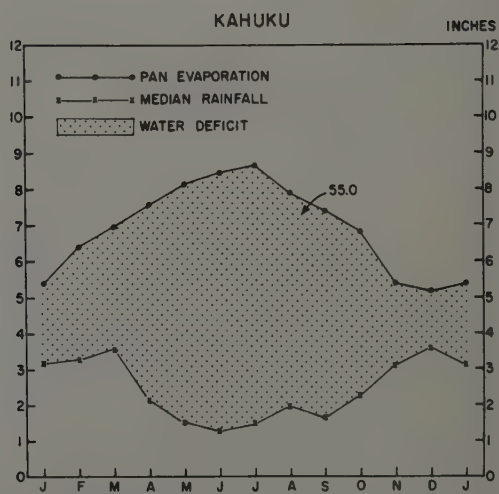


FIGURE 29. Monthly water balance chart at Kahuku.

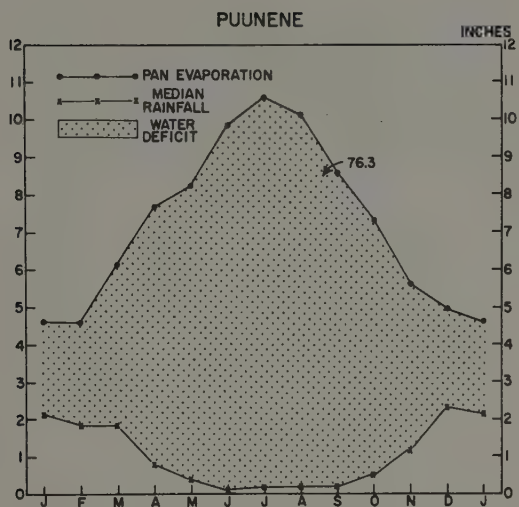


FIGURE 30. Monthly water balance chart at Puunene.

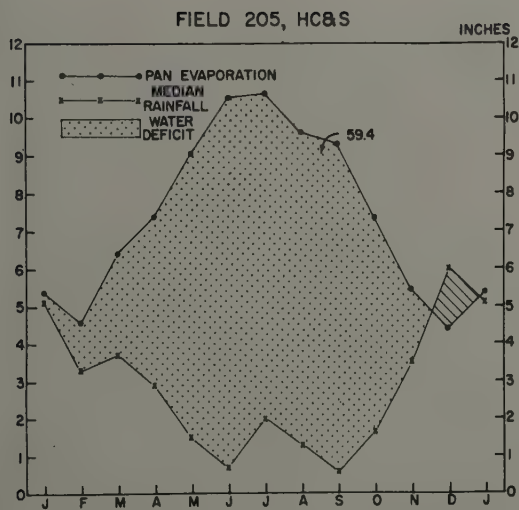


FIGURE 31. Monthly water balance chart at Field 205, HC&S.

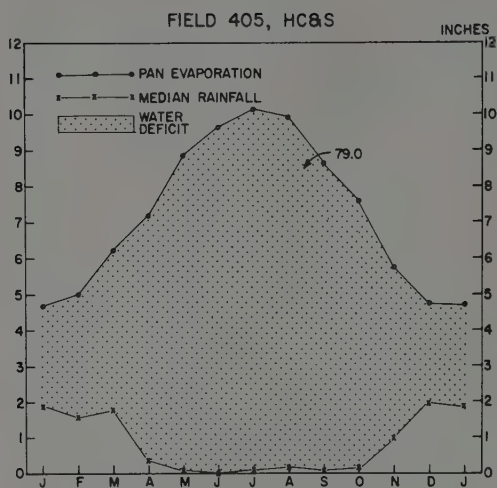


FIGURE 32. Monthly water balance chart at Field 405, HC&S.

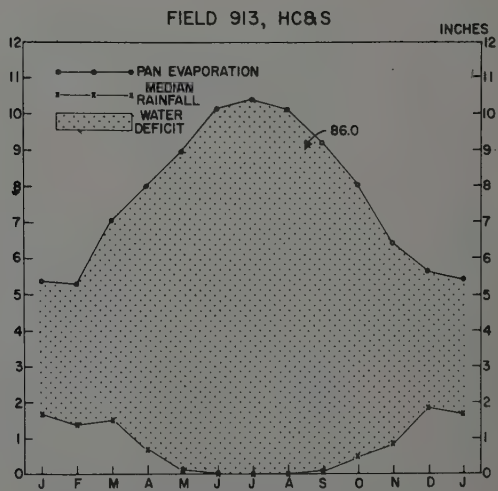


FIGURE 33. Monthly water balance chart at Field 913, HC&S.

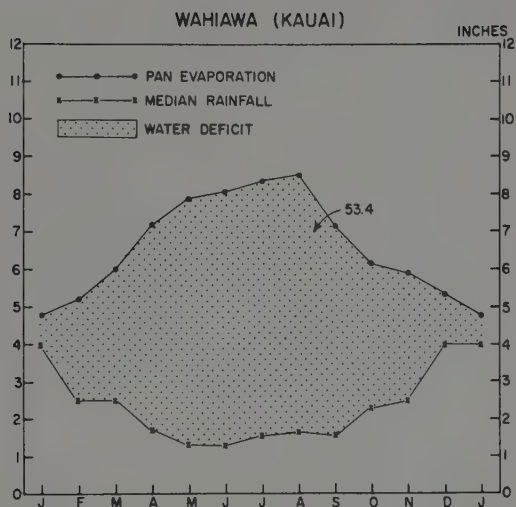


FIGURE 34. Monthly water balance chart at Wahiawa, Kauai.

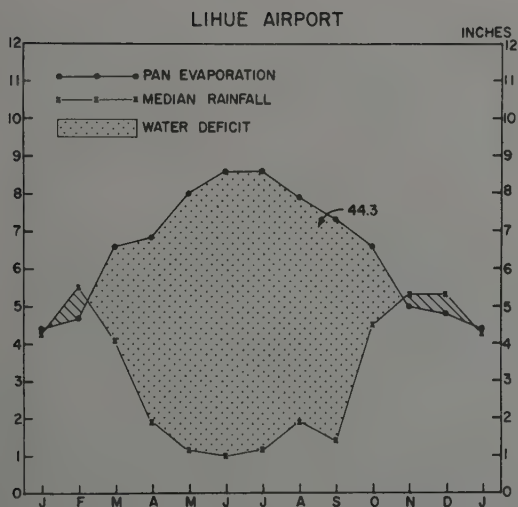


FIGURE 35. Monthly water balance chart at Lihue Airport.

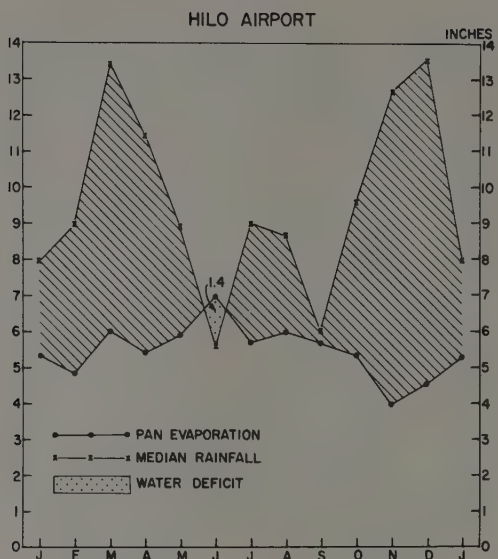


FIGURE 36. Monthly water balance chart at Hilo Airport.

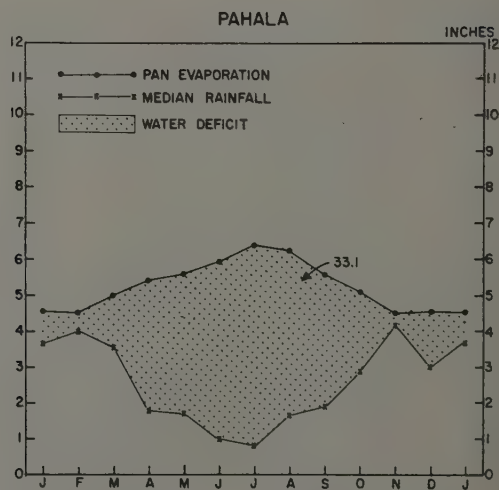


FIGURE 37. Monthly water balance chart at Pahala.

year crop is approximately 3.5 tons sucrose per acre on hillside land where the cane suffers from no other limitations. The water balance study, together with the yield information, would enable one to determine the economy of irrigation in marginal areas, where the application of water is not needed to avoid crop failures but may serve to increase the yield. The water balance study may also serve as a basis for assessing the current irrigation practices on the plantations.

SUGGESTIONS FOR FUTURE RESEARCH

This paper is an account of but a small part of the vast, intricate, and often controversial, subject of agricultural meteorology in general, and micro-meteorology of sugar cane in particular. Many problems remain obscure and the results of current research have yet to be fully applied to actual operation. After three years of experiment, it may be well to outline areas for future research.

1. Although the photochemical tubes are an accurate instrument, they break easily and their maintenance cost is rather high. The Physiology and Biochemistry Department of this Experiment Station has devised a light-integrator which is rigid and inexpensive; however, the instrument needs to be further checked for field use.

2. The sugar plantations in the Hawaiian Islands maintain one of the densest rainfall and temperature networks in the world but very few stations record wind speed and direction, which are essential for designing and scheduling of overhead irrigation. Pan evaporation records are also inadequate in a few areas.

3. Although we have three years' lysimeter data, it is desirable to have further corroboration of the consumptive use of sugar cane as derived from lysimeter experimentation. Also needing study is the controversial subject of the effect of moisture depletion on the evapotranspiration rate.

4. The MASI and Field L experiments will give further information for studies of the effect of irrigation on crop yield.

5. The use of the evaporation pan as a guide to irrigation is distinctly possible but several problems need to be solved. First, we should learn more about the effect of exposure and installation on pan evaporation. Second, we need to know (a) the storage capacity of the soil and (b) the portion of rainfall or irrigation water that is lost through runoff or leaching.

6. Of special importance to future work is a climatological mapping project. From the rainfall and evaporation records, we should be able to map the amount of monthly water deficiency of the cane areas. From the rainfall frequency records, we may also map the drought incidence. In this connection, van Bavel's work in the southern United States may be cited as an example, (41) although our maps will be on a much larger scale than his. Maps of rainfall variability and radiation distribution are also useful.

7. Another promising area for study is phenology, which concerns itself with the chronology of plant growth and its dependence on weather and climate. This is a very intricate problem because of the large number of variables in-

volved and, as such, it requires the cooperation of the plant physiologist, the soil scientist, and many others. In many of the micro-meteorological problems, work can be most rapidly advanced only by teamwork.

ACKNOWLEDGEMENT

The evapotranspiration study was initiated jointly by Mr. Doak C. Cox of the Geophysics Department and Mr. Robert B. Campbell of the Agronomy Department in 1957 before the author joined the Station. They have contributed greatly in setting up the experiments and in giving critical suggestions on the interpretation and presentation of data. The pan evaporation data at Makiki were furnished by Mr. Hugh Brodie. The Penman computation was carried out by Mr. George Darroch. Others who contributed in the experiments and in analyzing the data include Messrs. LeRoy Kosaka, Kenneth Kobayashi, Arthur Ching, T. Hayashi, and Larry Celiz.

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LIMING HAWAIIAN SUGAR CANE SOILS

A. S. Ayres*

The application of lime to Hawaiian sugar cane soils dates back to at least the final decade of the last century (5). Liming in those early years appears to have been largely restricted to the wetter areas of the island of Hawaii. Subsequently, the practice became more widespread, extending to soils which even now exhibit little if any acidity.

Variously applied in these liming programs were quicklime, or true lime (CaO), hydrated lime (Ca(OH)_2), and limestone (CaCO_3). Both local and imported materials were used for the purpose.

Local liming materials were obtained from limestone, or so-called coral reefs, which in an earlier era were raised conveniently above sea level. Also employed was coral sand obtained from Hawaii's beaches and which was often ground prior to application. Limestone from the chalk cliffs of Dover was also brought in by the shipload. An interesting aspect of this source of limestone is the flint which it contained as an impurity. This material is not native to Hawaii, hence its presence today in some sugar-cane fields reflects those early efforts to improve the base status of the soil.

Lime appears to have been employed in moderation. The usual application was 8-10 barrels per acre in the case of quicklime, or of from 0.5 to 3 tons per acre with hydrated lime or limestone (6). The lime was generally applied by spreader and worked well into the soil prior to planting. Applications were made at intervals of about seven years, which corresponded to the cycle of the cane crop. Lime was sometimes applied to ratoon fields.

It seems improbable that the quantities of lime applied to these highly buffered soils would have had much effect upon the degree of acidity. Nor is there any reason to believe that the planters were under any delusions in this regard. The limus initially employed as an indicator of soil reaction offered little indication of the quantity of lime required to achieve any predetermined degree of neutralization. In later years, the Vietch procedure for determining lime requirement was employed, but no effort appears to have been directed toward achieving a high degree of neutralization.

Many and varied were the arguments advanced in support of liming. It is not surprising in view of the advances in knowledge of soils and soil-plant relationships of the past fifty years that some of these theories are no longer tenable. The feeling appears to have been general that soil acidity *per se* was undesirable, not in harmony with good farming practice, and, therefore, should be corrected. In somewhat later years, undue emphasis upon the importance of soil acidity in relation to nitrification lent impetus to liming programs. No concern appears to have been expressed that calcium as a nutrient may have been a limiting factor of growth.

Whatever the motives for liming, agreement that sugar cane benefited from the treatment appears to have been unanimous. Typical is the reply of a Hilo

*Senior Agronomist, Experiment Station, HSPA.

Coast plantation manager more than fifty years ago to a question put to him regarding the benefit of this operation (5): "I have noticed that fields that have been limed compared with those that did not receive an application, were very much better; that there was a vast difference in the appearance of the cane---the cane was green, strong and healthy compared with the fields that had not been limed . . ."

Early Field Experiments With Lime

Efforts to place the value of lime in the production of sugar cane on a quantitative basis were made in the course of time by means of field experiments. Results of perhaps the earliest of such tests, conducted at Olaa during the period 1909-1911, are reported by Naquin (10). The data from this test (Table 1) indicate a gain of 0.88 ton sugar per acre at the highest level of fertilization, from the application of 2 tons of coral sand per acre. This was taken as a clear indication of the beneficial effect of liming.

Table 1. Results of early experiment with lime (1911) at Olaa Sugar Co., Ltd.

Complete Fertilizer	No Coral Sand			Coral Sand			
	Cane	Sugar	Gain in Sugar due to 500 lbs. C.F.*	Cane	Sugar	Gain in Sugar due to 500 lbs. C.F.*	Coral Sand**
(Lbs/A)	(T/A)	(T/A)	(T/A)	(T/A)	(T/A)	(T/A)	(T/A)
500	37.4	5.00		40.6	5.41		.41
1000	47.0	6.26	1.26	51.6	6.90	1.49	.64
1500	51.2	6.82	.56	57.7	7.70	.80	.88

*C.F. = Complete Fertilizer

T/A = tons per acre

**2 tons per acre.

Within a few years, additional tests with lime were initiated in other areas. In the twenty years that followed these earliest experiments, testing with liming materials was expanded to cover practically all of the acid sugar-cane soils of the Islands. Various forms of lime available for the purpose and amounts of the material ranging from very small quantities up to 18 tons per acre were investigated. Residual effects of lime were also studied.

The results of twenty-five of these experiments were reviewed by Verret in 1924 (12) and again in 1926 (13). The tests were conducted during the eight-year period immediately preceding the date of the initial report. Half of these experiments showed no gain whatever from lime. The remaining half showed slight gains, but in no instance was the increase considered significant. Average quality ratios were nearly identical: 7.99 with lime and 7.97 without lime.

In 1933 Verret again reviewed the status of the lime experiments (14) and included eleven tests not previously analyzed. Again there was little, if any, evidence of increased yields of sugar as the result of liming. Moreover, there

were indications that juice quality was generally better where lime was not applied.

Interest in liming sugar-cane soils all but vanished as the result of this overwhelming evidence that the operation was an unprofitable one. Sufficient interest remained, however, to move the Experiment Station to study further the effect of lime on juice quality.

A test with the objective indicated was conducted at the Manoa Substation and reported by Doty (4) in 1935. As with so many of the previous experiments, no gains resulted from lime, and juices were of poorer quality on limed than on unlimed soils. Part of a subsequent study by Ayres (1) involved liming large pots (2'x2'x2') of soil from the same area to pH 6.0. Under these conditions, modest increases in yield of cane were obtained from liming and juices were not adversely affected.

Calcium Status of Soils in Humid Areas

Ten years after Verret's final report on the lime experiments, Ayres (2) made a comprehensive study of the chemical properties of the humic and hydrol humic latosols of the Hilo and Hamakua coasts and Puna region of Hawaii. It was in these areas that the most intensive liming had been practiced and in which the majority of the lime experiments had been located.

This study revealed the presence of soils extremely low in exchangeable calcium, levels which have since been recognized as being indicative of extreme deficiency for sugar cane. It was shown, moreover, that reserves of calcium, as determined by fusion analysis, were also very meager--in some instances as low as 0.10 per cent, and that more than half of the total calcium was present in exchangeable form. Calcium saturation in some areas was found to be below 1 per cent.

Reconciliation of the findings of this study with the results of the earlier lime experiments was difficult. With the memory of previous tests still fresh in the minds of plantation agriculturists, the work afforded little stimulation in the direction of new experiments with lime. Unfortunately, in the absence of field tests, there was no way at the time to calibrate levels of soil calcium in terms of crop response. This was to come at a later date.

Interestingly enough, evidence from the field in support of the calcium picture in these soils, as portrayed by soil analysis, came initially not from experiments with lime, but from tests comparing different forms of phosphate. In 1949, plant crops of two Hilo Coast experiments were harvested which showed highly significant gains of 1.6 and 1.8 tons sugar per acre in favor of superphosphate over ammonium phosphate. These differences in yield were interpreted as indicating deficiencies of calcium in the experimental areas.

Analysis of soil samples from the zero phosphate plots of these experiments for exchangeable calcium revealed levels of only 60 and 80 pounds Ca per surface acre-foot. Since an intensive fertility survey made by the Experiment Station* at this time, together with the study already referred to (2), showed

*Report of the fertility survey of Hilo Coast plantations to S. L. Austin, Hilo Transportation and Terminal Company, April 5, 1950.

thousands of acres of Hilo Coast and Puna soils to contain less than the amounts of calcium indicated, a calcium problem of serious and far reaching proportions was implied.

Current Field Experiments With Limestone and Gypsum

Plans were immediately made to reinstitute the lime testing program abandoned twenty years before, and by 1951 the first tests designed to measure the effect of limestone and gypsum on yield of sugar had been initiated. Testing with these materials has proceeded since that time at an accelerated rate and at the time of writing, ten years later, some forty such experiments have been harvested. Quite unlike the earlier tests with lime, many of these have shown significant increases in sugar as the result of treatment. Examples of these increases are shown in the form of yield-response curves in *Figure 1*. Indicated also in the chart are respective levels of calcium initially present in the experimental areas. The shape of the curves in this figure implies that, despite large gains from treatment, optimum yields of sugar were not achieved.

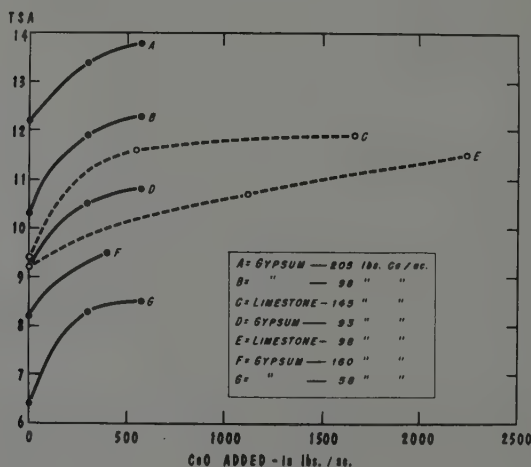


FIGURE 1. Increases in yield of sugar resulting from the addition of calcium-containing materials. (Values in box refer to initial levels of soil calcium)

With the dawning realization that thousands of acres of sugar-cane land in Hawaii are seriously deficient in calcium has come the urge to correct this condition as quickly and effectively as possible. This correction is being accomplished by moderate additions of ground limestone to areas shown by soil or plant analysis to be deficient with respect to this element. Applications of limestone generally are of the order of 1000-3000 pounds per acre and, for

the most part, are broadcast and plowed into the soil immediately prior to planting. Thus, after a lapse of a quarter of a century, liming of sugar cane soils is once again in vogue in Hawaii.

In view of the unquestionable gains in yield of sugar from calcium-containing materials evidenced in the recent experiments, one naturally wonders at the complete absence of corresponding increases in the earlier tests. The answer, seemingly, is a simple one and is associated with the three following related facts:

First, until about the time the initial testing with lime ceased, that is about 1935, liming had been widely practiced in the more humid sugar-cane areas. With failure of the earlier experiments to respond to liming, this practice ceased and thereafter calcium was applied only incidental to the use of phosphate fertilizers.

Second, coincident with this change in the calcium economy of the soil was another change of perhaps equal importance---- abandonment of the use of nitrate of soda in favor of ammonium-containing nitrogen carriers. As is well recognized, hydrogen ions formed in the conversion of ammonium to nitrate, a process which takes place within a short time following addition of the fertilizer to the soil, effectively lower the level of calcium under conditions conducive to leaching.

Finally, there is the factor of mechanization in the harvest field, which as practiced in Hawaii, is very destructive of soil fertility.

The Critical Level for Soil Calcium

For an analysis of a soil for calcium to be of practical value to the agriculturist, it is essential that he know the level of soil calcium below which the addition of calcium may be expected to result in increased yields and above which it may not. This point, the so-called critical level, is illustrated in *Figure 2*, where are represented the harvest results of all available experi-

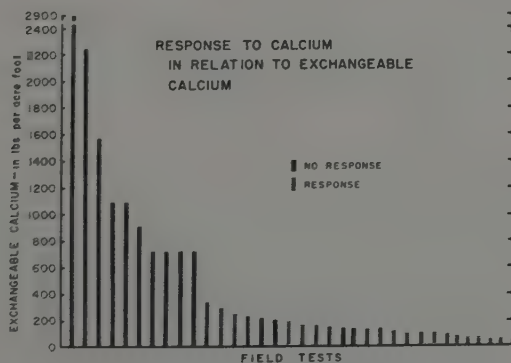


FIGURE 2. Response to calcium in relation to initial level of exchangeable calcium. Indicated responses possess statistical significance.

ments suited to the purpose at hand, together with corresponding initial levels of soil calcium. These experiments, conducted on soils ranging in calcium content from about 50 to nearly 3000 pounds per acre and totaling thirty-four in number, are arranged from left to right in the chart in order of decreasing level of soil calcium. All responses indicated possess statistical significance.

The chart reveals a complete absence of response to additions of calcium to soils containing in excess of about 400 pounds exchangeable calcium per acre-foot. Below this level, all but four experiments showed significant gains and even those four showed increases of 0.4, 1.5, 1.6 and 1.7 TSA. On the basis of present evidence, the critical level for soil calcium is therefore taken to be in the vicinity of 400 pounds per acre.

When the increases in sugar obtained in the experiments represented in *Figure 2* are plotted against respective initial levels of soil calcium, the relationship illustrated in *Figure 3* is obtained. Here it will be seen that at very low levels of soil calcium, impressive increases in yield resulted from the addition of calcium. With increasing level of soil calcium, gains gradually diminished and approached zero at around 1000 pounds Ca per acre. The indicated gains in sugar on soils containing over 400 pounds per acre do not conflict with the concept of this value as the critical level for calcium, since the question of significance does not enter here.

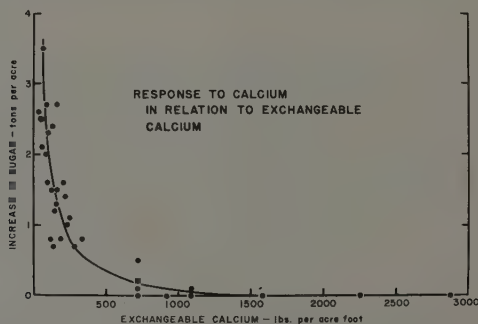


FIGURE 3. Curve relates increases in yield from additions of calcium to initial level of exchangeable calcium.

Doubtless, plantations will be interested in lesser increases in sugar than those required for significance and may therefore wish to maintain the supply of soil calcium at a point above the critical level. This should not prove difficult to achieve in view of the comparatively low cost of limestone and its resistance to leaching.

Critical Levels for Plant Calcium

The presence of field experiments showing response to additions of calcium has made possible determination of the critical level for this element,

not only in the soil, but also in cane tissue. For the two portions of the plant ordinarily analyzed for calcium, namely the leaf sheath and the 8-10 internode section of the stalk, critical levels are taken as 0.15 and 0.05 percent, respectively.

Effects of Heavy Liming on Yield of Sugar

The increases in yield which have just been considered are seemingly the result of having largely overcome deficiencies of soil calcium and are not the result of decreased acidity. Gypsum, which possesses no neutralizing power whatever, produced as large gains as equivalent amounts of limestone. Moreover, the quantities of limestone employed were quite moderate, hardly sufficient to have had much effect on the pH of these highly buffered soils. On top of this, response was obtained only where soils were very low in calcium.

The possibility that the productivity of acid soils adequately supplied with calcium may be improved by applications of limestone has not, however, been overlooked. Numerous field experiments have been initiated within the last few years embracing amounts of limestone ranging up to 23 tons per acre and calculated to effect practically complete neutralization of the soil. The purpose of this series of tests has not been to determine the need for calcium as a nutrient; in fact, the tests have not included zero calcium plots. Rather, the design has been to measure the integrated effect on yield of numerous other changes in soil properties presumed to be brought about by heavy liming. To date there is little, if any, convincing evidence from these experiments that the productivity of sugar-cane soils is appreciably enhanced by liming beyond the rate necessary to meet the requirement of the crop for calcium.

Effect of Heavy Liming on Soil Properties

Neutralization of soil acidity, even in a degree, may markedly affect chemical, biological and, indirectly, physical properties of soils. Some of these effects have been recently studied in this laboratory* and it will be worthwhile to consider them at this time, even though their influence on yield of sugar has not been evaluated.

Soil Reaction

Hawaiian soils are principally clay soils with moderate to high cation exchange capacities; hence, substantial quantities of lime are required to raise the pH significantly. The amount of lime necessary to achieve a given pH is a function of the degree of acidity of the soil, as well as the nature of the soil. Curves illustrating the effect of lime on the pH of several acid soils of various great soil groups are shown in Figure 4.

*Most of the work to which reference will be made has been carried out by Harold Hagihara, Associate Agronomist.

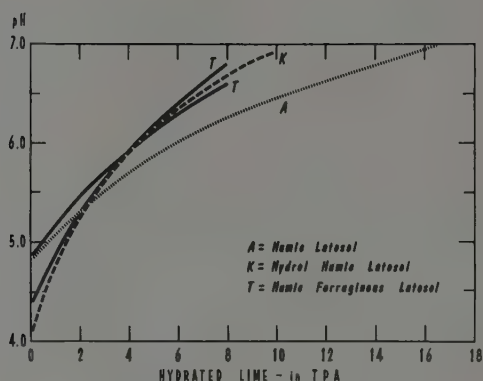


FIGURE 4. Titration curves for low-calcium soils.

For convenience, calcium hydroxide rather than limestone was employed in the preparation of the curves. Accordingly, the relative neutralizing power of these two materials would have to be considered where limestone is employed, and curves such as these are used only as guides in the liming operation. Limestone possesses somewhat less neutralizing power than the hydroxide; moreover, different sources of commercial limestone may differ appreciably in this respect.

Limestone, particularly where heavy applications of this material are made, is generally broadcast and plowed into the soil prior to planting. In Table 2 are shown pH values from experiments on several humic and hydrol humic latosols in relation to quantities of limestone applied. The data represent the reaction of the soil at harvest, or approximately two years after liming.

Table 2. pH values of soils in relation to rate of application of limestone.

Plantation	Great Soil Group	Limestone T/A	Depth in.	pH
Hilo Sugar Co.	Hydrol Humic Latosol	0	0-12	5.4
		2	"	5.6
		5.5	"	6.2
		11	"	6.6
Onomea Sugar Co.	Hydrol Humic Latosol	0	0-12	5.0
		2	"	5.1
		5.5	"	5.5
		11	"	5.8
Paauhau Sugar Co.	Humic Latosol	0	0-12	5.1
		6	"	6.0
		15	"	6.5
		23	"	6.7

Nutrient Balance

A good deal has been heard in recent years regarding the probable adverse effect of heavy liming upon the nutrient balance in soils. The argument has been that the addition of 10-20 tons of limestone per acre to a soil normally containing perhaps 400 pounds of exchangeable calcium in the surface acre-foot, with half this amount of potassium and magnesium, would create such a state of nutrient imbalance that productivity of the soil would be impaired.

The results of a recent study with lime at Makiki suggest that such concern is overdrawn. Two very low-calcium soils from Onomea and Laupahoehoe were placed into pots and limed in increments to neutrality with amounts of limestone ranging up to 20 tons per acre. Sugar cane grown in these soils showed no ill effects of treatment at any level, as judged either by appearance or weights of millable cane at harvest. The relationship between rate of liming and yield in the case of the Onomea soil is illustrated in *Figure 5*. A curve nearly identical in form was obtained with the Laupahoehoe soil.

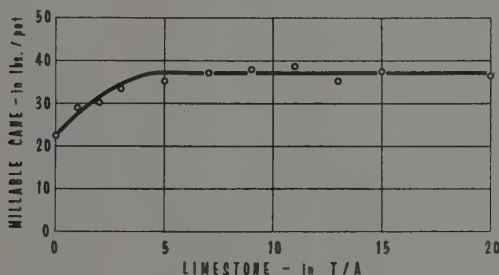


FIGURE 5. Heavy liming produced no adverse effect upon yield of cane in this pot study. (Onomea Sugar Company soil.)

Retention of Potassium

It was shown in laboratory studies by Ayres and Hagihara (3) some ten years ago, that the least saturated of the humic and hydrol humic latosols possess almost negligible capacity to retain potassium under conditions conducive to leaching when this element is applied in the form of the muriate. In subsequent studies with other soils, it was shown by these workers that where the supply of calcium is abundant, leaching of potassium muriate does not take place. The ability of soils to retain this form of potassium appears to be much more a function of calcium content than of soil type. The influence of soil calcium on the leachability of KCl from a number of soils from Kohala is illustrated in *Figure 6*. A similar relationship has been observed with very different soils from Lihue Plantation.

In view of this direct relationship between soil calcium and retention of potassium, it might be expected that the addition of lime to soils extremely low in calcium would enhance their ability to retain potassium. The results of such a study with an essentially unsaturated hydrol humic latasol from Laupahoehoe

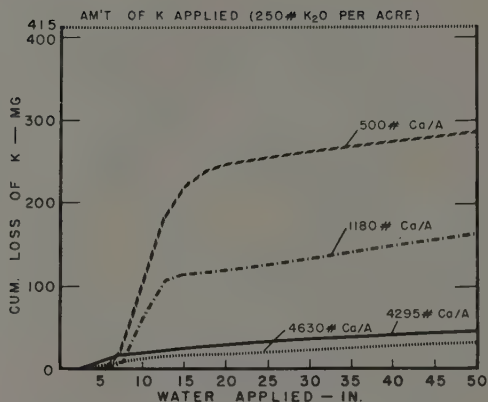


FIGURE 6. Susceptibility of potassium muriate to leaching is related to level of exchangeable calcium.

are illustrated in *Figure 7*. Here it will be seen that the minimum application of 6 tons of limestone per acre substantially reduced the loss of potassium, and that successive equal increments of limestone reduced losses still further, although in lessening degree. An even greater effectiveness of limestone in reducing loss of KCl is indicated for another Laupahoehoe soil in *Figure 8*, where it will be seen that an application of only 2 tons per acre of this material cut the loss by about one-half.

Solubility of Aluminum

It was shown half a century ago by Kelley, McGeorge and Thompson (9) that many Hawaiian soils are unusually high in aluminum content. This view

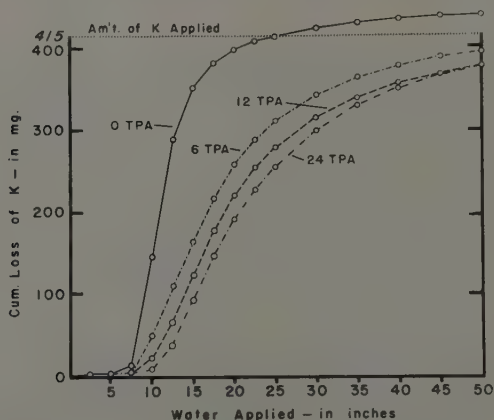


FIGURE 7. Lime reduces susceptibility of potassium muriate to leaching on low-calcium soils.

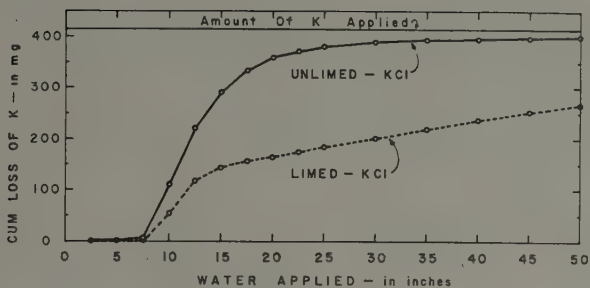


FIGURE 8. Loss of potassium from the muriate is effectively retarded by an application of 2 tons limestone per acre.

was subsequently confirmed through intensive study of soil profiles taken in connection with the Hawaii Soil Survey in 1935-36 (7, 8).

Since the solubility of aluminum is a function of pH, the fear has frequently been expressed that owing to the high aluminum content of Hawaiian soils, the presence of toxic amounts of this element in soluble form may result from low pH values. Concern has been felt particularly with respect to the more highly weathered soils from which silica has been largely removed and where, as a result, aluminum is present principally in the form of hydrous oxides.

The effect of pH on the solubility of aluminum in normal ammonium acetate for a wide selection of Hawaiian soils is shown in Figure 9. These results do not purport to show levels of soluble aluminum that might be expected to be

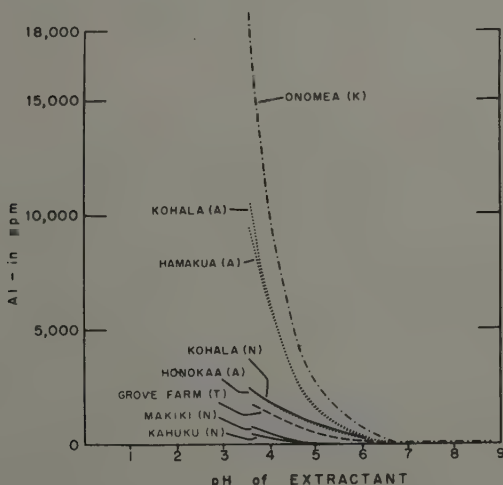


FIGURE 9. Curves indicate increasing solubility of soil aluminum with decreasing pH.

present in the respective soils at the pH values indicated. Ammonium acetate itself has a solubilizing action on soil aluminum, an action that diminishes with decreasing concentration of the acetate. The data serve rather to illustrate the strong influence of pH on the solubility of this element and to differentiate between soils with respect to their potentialities in this direction.

With the solubility of aluminum increasing as it does with increasing soil acidity, it would logically be expected that any trend in this direction might well be counteracted by liming, which raises soil pH. Table 3 shows that the application of limestone does indeed lower the solubility of soil aluminum for two hydrol humic latosols. Here the downward trend in extractable aluminum with increasing limestone applications is clearly evidenced.

Table 3. Extractable aluminum in two hydrol humic latosols diminished by application of limestone.

Soil	Limestone (T/A)	Extractable Aluminum* (ppm)	Soil	Limestone (T/A)	Extractable Aluminum** (ppm)
Onomea	0	2060	Laupahoehoe	0	3190
"	4	1800	"	5	2880
"	8	1580	"	10	2410
"	16	1510	"	20	2100

Soils extracted with N-NH₄OAc, pH 4.8

*3 months after liming

**4 months after liming

As has already been noted, significant increases in yield of sugar from heavy liming over light liming have not as yet been proved. This suggests that soluble aluminum was not present in toxic quantities in the soils tested. It is anticipated that further research in this area will clarify this point.

Solubility of Manganese

Some Hawaiian soils, notably the low humic latosols, are unusually high in manganese oxides. These soils are, in fact, set apart from other latosols partly on this basis. Under conditions such that these soils become increasingly acid, manganese is converted in part from inert oxide forms to the active manganous form. In this reduced state, manganese is readily taken up by plants. Quantities of manganese in this absorbable state, as measured by extraction with N-NH₄OAc, pH 4.8, have been found in this laboratory to exceed 1000 pounds in the surface acre-foot of soil. Since conversion of manganese from inactive forms to the active form takes place in part as a result of increased acidity, liming may logically be considered a means of correcting this condition. Indeed Sherman and Fujimoto (11) have demonstrated the effectiveness of lime in reducing the level of soluble manganese in certain Hawaiian soils.

In the hydrol humic and some of the humic latosols, in which interest in heavy liming is centered, the situation with respect to manganese is very different than in the low humic latosols. In the former, levels of active manganese are very low, so low in fact that symptoms of manganese deficiency have been

known to appear on the leaves of sugar cane, symptoms which disappear upon addition of manganous sulfate to the soil.

With some of these soils, conceivably, heavy liming might reduce already limited supplies of available manganese to a critically low level of the element. Studies in this laboratory have shown that liming tends to diminish manganese availability in soils of this type, as may be seen in *Table 4*. To the author's knowledge, manganese deficiency as a result of liming has not been observed in the areas under test.

Table 4. Level of extractable manganese in two hydrol humic latosols reduced by liming.

Soil	Limestone (T/A)	Extractable Manganese* (ppm)	Soil	Limestone (T/A)	Extractable Manganese* (ppm)
Onomea	0	28	Laupahoe	0	14
"	4	22	"	5	11
"	8	19	"	10	9
"	16	17	"	20	8

*Manganese extracted with N-NH₄OAc, pH 4.8, 7 months after liming.

Mineralization of Organic Nitrogen

Amounts of nitrogen present in the surface foot of Hawaiian sugar-cane soils range, according to data reported by Ayres in 1943 (2), from about 3000 to 15,000 pounds per acre. Substantial quantities of nitrogen are also present in the subsurface layers. Through the activity of microorganisms, this nitrogen is continually undergoing conversion to inorganic forms. Simultaneously, inorganic soil nitrogen is being assimilated into organic forms by both microorganisms and higher plants. At any moment, the proportion of the total soil nitrogen present in forms which are available to sugar cane is extremely small--less than 1 per cent.

The activity of the microorganisms responsible for the mineralization of organic nitrogen has been shown by microbiologists to be in part a function of soil pH, the rate of decomposition being greater in neutral and slightly acid soils than in more acid soils. Accordingly, it might be expected that substantial liming of acid soils high in organic nitrogen would result in an enhanced rate of liberation of the element.

The matter is currently under study in this laboratory, and the results obtained to date with a Laupahoe soil are shown in *Figure 10*. For the eight-month period represented, with the unlimed soil the increase in inorganic, or available, nitrogen totaled in the vicinity of 35 ppm, which is the equivalent of 65 pounds per acre. Where lime was applied, the rate of release was greater, increasing with rate of application to a maximum of about 125 ppm or 225 pounds per acre. Somewhat lower results were obtained when an Onomea soil was similarly limed and incubated for a comparable period.

This stepped-up release of nitrogen as a result of liming could have considerable impact on the nitrogen economy of the cane crop. Liberation of ni-

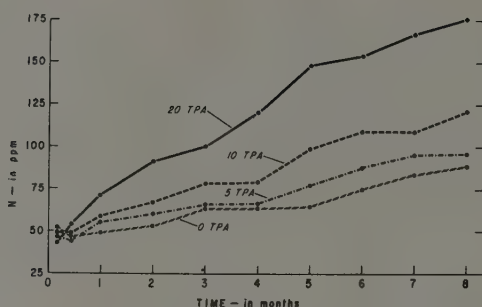


FIGURE 10. Liming acid soils increases rate of mineralization of organic nitrogen.

trogen during the first season might well prove desirable, possibly resulting in economy in nitrogen fertilization. Release of substantial amounts of nitrogen late in the second season might, on the other hand, unduly prolong vegetative growth, thereby resulting in poor juices. Thus, if heavy liming were to become a plantation practice, some modification of existing nitrogen fertilization practices would be desirable. This effect of liming would be expected to be greatest in humid areas where control of soil moisture is not possible. The poor juices so frequently associated with heavy liming probably can be accounted for on this basis.

Effect of Additions of Calcium on Plant Uptake

Where calcium-containing materials are applied to soils deficient with respect to this element, substantial increases take place in plant calcium. In decreasing degree, this may be true also even after the deficiency has been met. Some typical examples of the effect of additions of calcium on the level of this element in sugar cane are shown in *Table 5*.

Table 5. Effect of calcium-containing materials on level of plant calcium.

Plantation	Calcium (lbs. per acre)	Calcium in 8-10 stalk (%)
Laupahoe Sugar Co.	0	.030
	400 as CaO from limestone	.097
Laupahoe Sugar Co.	0	.023
	400 as Ca from gypsum	.064
Hakalau Sugar Co.	560 as CaO*	.072
	2675 "	.14
	10610 "	.15
	18550 "	.15
Hilo Sugar Co.	570 as CaO*	.10
	2690 "	.12
	6400 "	.12
	12239 "	.14
Paauhan Sugar Co.	560 as CaO*	.11
	7520 "	.16
	17960 "	.15
	27240 "	.16

*From gypsum, superphosphate and limestone.

Leachability of Liming Materials

An aspect of liming that merits attention, but upon which data obtained at the Experiment Station are very meager, is the susceptibility of liming materials to loss by leaching. The question is important since it is related to the duration of the effect of liming.

In Figure 11 is indicated the cumulative loss of calcium from gypsum applied to the surface of a 1-foot column of soil and leached with 50 inches of water over a period of one month. The soil employed in this study was a humic latosol from Laupahoehoe. The figure shows that gypsum was readily leached from the soil, less than one-fifth of the application remaining in the column at the end of the test.

The results of leaching a similar soil that had been treated with limestone at the rate of 2 tons per acre is illustrated in Figure 12. In this test the limestone was mixed with the soil and the soil allowed to stand in a moist condition for 1.5 months prior to initiation of leaching. This was done in order to foster the reaction between limestone and soil. The leaching process in this instance was more drastic than with the gypsum, amounting to 75 inches of water, the operation being carried out over a period of 1.5 months. The figure reveals limestone to be far less subject to leaching than gypsum. For the maximum degree of leaching, loss of calcium from limestone amounted to only about 10 per cent of the quantity applied.

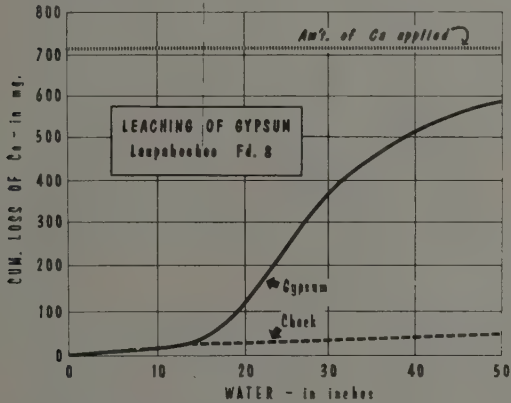


FIGURE 11. Calcium applied to the soil as gypsum is subject to loss by leaching.

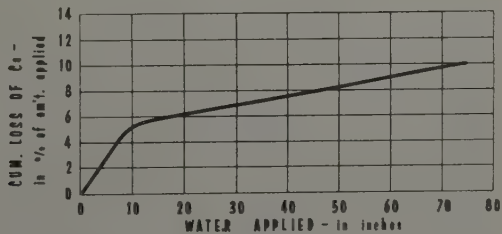


FIGURE 12. Calcium in limestone is resistant to leaching.

Discussion

When a soil has been found to be deficient in calcium and it is desired to correct this condition, the question naturally arises as to what the application of limestone should be. In seeking an answer to this question it will be assumed that the goal in liming is solely to compensate for any deficiency of the soil with respect to calcium as a nutrient and not to attempt to achieve unproven benefits associated with changes in soil pH *per se*.

This is an important economic consideration for, if the goal is to raise appreciably the pH of the surface soil (e.g., from pH 4.5 to pH 6.5), many tons of limestone per acre would be required. Such a practice cannot be supported by the evidence obtained in field trials. There is ample support, however, for the practice of applying liming materials or non-neutralizing calcium carriers in relatively low amounts to correct calcium deficiency.

The rate of application of limestone necessary to achieve the optimum yield of sugar on a particular soil is dependent upon the initial supply of soil calcium. The desirable application of limestone for a soil containing 100 pounds Ca per acre, for example, will be much larger than for a soil possessing a Ca level of 500 pounds per acre. The amount of Ca-containing material to apply as an adequate correction measure will depend also on factors such as placement, properties of the material (e.g., analysis, fineness of grinding), and frequency of application.

Before proceeding further on the question of application rates, it will be worthwhile to note that the increases in sugar indicated in *Figure 3* do not represent gains from a given application of calcium, nor necessarily from optimum amounts of calcium, but rather from whatever constituted the highest rate of application in the particular test. That maximum yields of sugar, commensurate with other factors in the experiments, were in many cases not achieved has already been noted in connection with discussion of the response curves in *Figure 1*. Here it will be seen that, generally speaking, additional sugar might well have been obtained from somewhat higher rates of gypsum or limestone than those employed, even though 90 per cent or more of maximum yield appears to have been reached.

As an ideal basis for predicting optimum liming rates, complete response curves should be available for a wide range in levels of available soil calcium. However, in view of the evidence already at hand, it does not appear practicable to expend the effort and expense necessary to achieve this goal.

The associated field and laboratory studies aimed at assessing the calcium status of sugar cane soils have established: (1) a reasonable and workable procedure for determining the degree of adequacy or deficiency of soil calcium; and (2), a basis for estimating approximately the amounts of limestone or other calcium material needed to correct the deficiencies noted. The plantation is concerned not only with initially correcting known deficiencies, but also with a realistic program of calcium maintenance over a long period. If limestone is to be applied only at planting, the application should be sufficiently large to meet not only any immediate need for calcium, but also to compensate for uptake of the element by the several cane crops in the cycle, as well as for loss of calcium by leaching during the period indicated.

Plantations with a calcium problem are familiar with the graphic system of reporting soil calcium data which has been employed for some years by the Station. Indicated on this form are zones of adequate and inadequate calcium supply as well as the relationship between recommended application of calcium to the immediate crop and level of soil Ca as shown by analysis.

This chart has been modified in several respects in light of the additional calcium-yield data now available. Zones of sufficiency and deficiency have been deleted. These zones, based upon the presence or absence of significant yield increases from additions of calcium, are no longer necessary in view of the more useful relationship which has been established between soil Ca and response (*Figure 3*). This relationship is delineated in the modified chart in the form of a curve relating soil Ca to recommended application of calcium. Finally, in its new form the chart has two base scales instead of one. As before, one of these pertains to additions of calcium to meet the need of the immediate crop; the other relates to rates at planting where there will be no further addition of calcium until termination of the crop cycle.

The modified calcium chart (*Figure 13*) reflects our present thinking regarding applications of calcium-containing materials for the purpose of meeting the need of the cane crop for this element. In considering the need for additional calcium, that present in raw rock and in super and treble superphosphates should not be ignored. Soil analyses at intervals of several crops should serve as a check on the adequacy of the liming program.

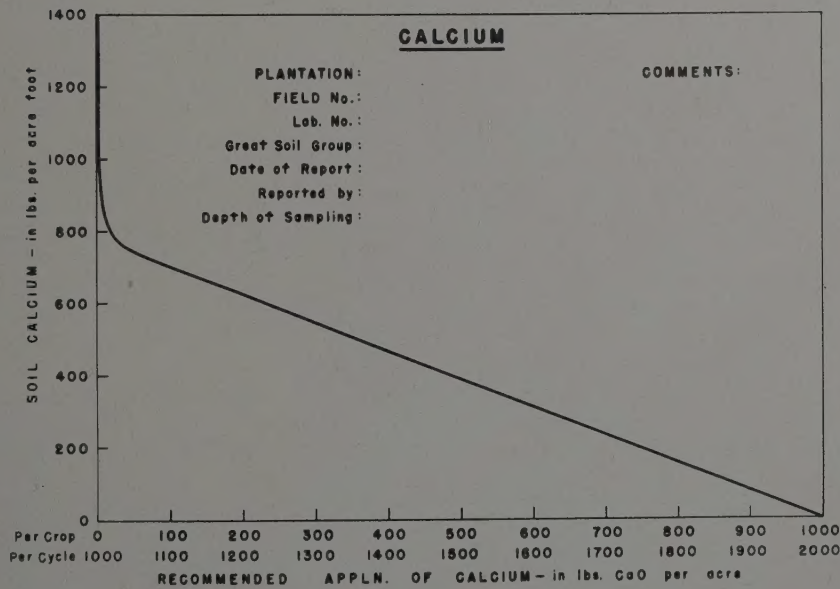


FIGURE 13. Recommended application of calcium is based on level of soil (exchangeable) calcium.

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